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ABSTRACT

Schematism is proposed as part of an epistemological framework for constructing and employing scientific knowledge. Within this framework, it is proposed that a concept of physics can be explicitly defined in a scientific theory by a schema that includes: (1) the domain of the concept; (2) its organization, i.e., the relationships between this particular concept and other concepts; (3) it quantification, i.e. its measurement according to well-defined laws and rules; (4) its expression, i.e., the set of words, depictions and mathematical representations denoting it; and (5) its employment, i.e., the ways it can be used to deal with physical situations that belong to its domain, and to construct and employ scientific knowledge. The schematic structure of the concept of force is presented for illustration, and results of its application in training two groups of Lebanese students are outlined. Contains 46 references. (Author)

Schematic Structure of Scientific Concepts

The Case of Physics

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Abstract

Schematism is proposed as part of an epistemological framework for constructing and employing scientific knowledge. Within this framework, it is proposed that a concept of physics can be explicitly defined in a scientific theory by a schema that includes: (a) the *domain* of the concept, i.e., the set of physical entities and/or the corresponding property that the concept represents, (b) its *organization*, i.e., the relationships between this particular concept and other concepts, (c) its *quantification*, i.e., its measurement according to well-defined laws and rules, (d) its *expression*, i.e., the set of words, depictions and mathematical representations denoting it, and (e) its *employment*, i.e., the ways it can be used to deal with physical situations that belong to its domain, and to construct and employ scientific knowledge. The schematic structure of the concept of force is presented for illustration, and results of its application in training two groups of Lebanese students are outlined.

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Student beliefs about physics concepts

Educators and concerned groups have been worried lately about the state of scientific literacy among the general public (AAAS, 1990, 1993; NCEE, 1983). Some have long been arguing that a discipline like physics "should form part of the intellectual arsenal of any educated citizen" (PSC, 1972). Nevertheless, more than three quarters of U.S. high school students still graduate without having taken any physics course (NCES, 1994), and those who do take physics often complete their courses with little understanding of the covered material (AAAS, 1990; Halloun & Hestenes, 1985a, 1985b; Hestenes et al., 1992; McDermott, 1993). Physics teachers at all levels are still expressing the same complaint that Swann voiced in 1950, that a physics student "passes his [or her] tests frequently alas, with very little comprehension of what he [or she] has been doing" (Swann, 1950).

Student knowledge of physics "can best be described as [consisting of] bundles of loosely related and sometimes inconsistent..., vague and undifferentiated concepts" that are incompatible with scientific theory (Halloun & Hestenes, 1985b). Research shows that there are substantial numbers of students who often hold one or more of the following beliefs that physics concepts are (Halloun, 1995a):

1. ***fictitious***; they are often unrelated to the physical world;
2. ***mathematical***; they constitute a subset of mathematics and not a separate class, and thus operating with them is just like operating with mathematical symbols and formulas;
3. ***situation-specific***; a concept that represents a given object or a property of that object cannot represent another object in the same manner;
4. ***theory-specific***; a concept that belongs to one branch of physics does not necessarily belong to another, and if it does, it would have a different meaning and a different utility;
5. ***loosely related***; they are amassed like a heap of stones with no coherent structure;
6. ***arbitrarily quantified***; there are no systematic criteria, say, for deciding whether a concept is scalar or vectorial, or for specifying its dimensions and units;
7. ***uniformly operable***, especially in the sense that all concepts can be subject to all the same mathematical operations (e.g., adding temperatures or magnitudes of non parallel vectors);
8. ***interchangeable***; different physics concepts (like velocity and acceleration) can be used to represent the same property;
9. ***idiosyncratic***; physicists, like ordinary people, can have different interpretations of the same concept of physics;
10. ***arbitrarily employed***; they are applied by trial and error or following rules of thumb.

Teachers more than students are to be blamed for these beliefs about physics concepts. A concept of physics is often inadequately presented in traditional instruction, and poorly related to other concepts in coherent structures such as models and theory (Halloun, 1995a; Halloun & Hestenes, 1985b; Hammer, 1994; McDermott, 1993; Reif & Allen, 1992; Reif & Larkin, 1991).

A concept is to scientific theory what a quark or an electron is to the standard model of an atom. The standard model cannot be understood without understanding first the nature and properties of the elementary constituents of an atom. Similarly, a scientific theory cannot be understood without understanding the structure of concepts, its fundamental constituents.

Only recently, have science educators recognized the need to revamp our ways of presenting individual concepts and relating them to each other, so that they be at the reach of students.

In this paper, I discuss briefly major modes that some science educators have been advocating recently for presenting scientific concepts. Then I outline an epistemological framework in the context of which I propose a *schematic structure* of physics concepts that I illustrate with the concept of force. Finally, I briefly report on the results of implementing this structure in training two samples of Lebanese students.

Available modes of concept presentation

Student beliefs listed above are not particular to physics. They figure probably in all scientific disciplines. Alerted to the gravity of the effect of such beliefs on understanding scientific theory, some science educators have proposed recently new ways for presenting scientific concepts. Below is a brief review of their major proposals, especially those that have received some attention in the physics community.

Hierarchical Structures

Eylon and Reif (1984) proposed to structure physics concepts in hierarchical organizations in order to facilitate student "performance on scientifically relevant recall and problem-solving tasks". Figure 1-a shows a general schematic diagram of such organizations (Eylon & Reif, 1984) which is adapted in Figure 1-b to organize principles of classical mechanics hierarchically (Reif & Heller, 1982).

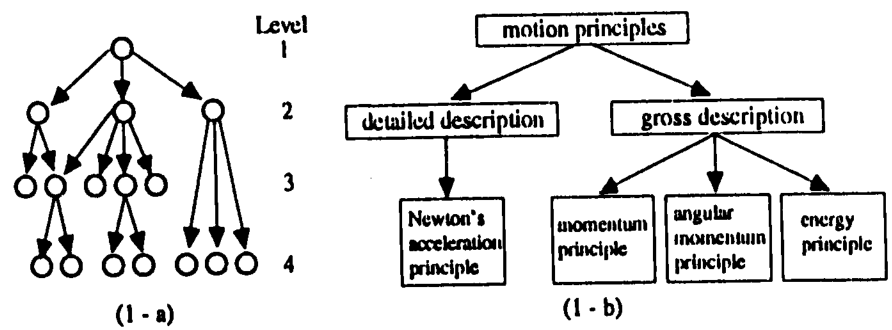


Figure 1: Schematic diagram of (a) a general hierarchical knowledge organization (Eylon & Reif, 1984), and (b) its adaptation to classical mechanics principles (Reif & Heller, 1982).

A number of college students were trained to structure their knowledge in different hierarchical organizations and employ them in solving classical mechanics problems. High ability students were able to benefit by such organizations, and perform "appreciably better" after training on tasks of recall and problem solving. However, "subjects with lower physics grades seemed less able to assimilate and use a hierarchical organization" (Eylon & Reif, 1984).

Concept Mapping

Concept mapping was proposed as a tool for learning science, conceptual change, and instructional design (Novak, 1990). In a concept map, students depict a number of related

concepts in a hierarchical representation similar to that shown in Figure 1-a. The most general or most inclusive concept is placed at the top of the hierarchy (level 1), followed in lower levels by successively less general or less inclusive concepts. The lines joining different concepts are labeled with the "linkage meanings" (Novak et al., 1983).

Roth and Roychoudhury (1993a) reported on the use of concept maps in a senior level high school physics course. Figure 2 shows a concept map drawn by a participating student to organize some concepts on light. The authors stated that some students drew concept maps that "illustrated hierarchical ordering that complied with canonical (standard) science". However, they reported that student "scientifically incorrect notions become ingrained and go unchallenged" (Roth & Roychoudhury, 1993a).

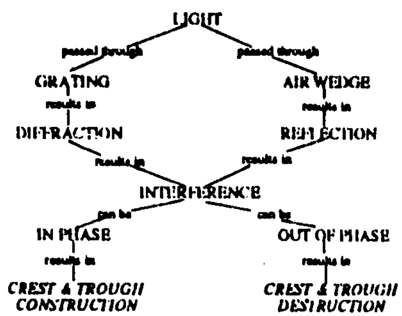


Figure 2: Concept map drawn by a student for linking concepts about light (Roth & Roychoudhury, 1993a).

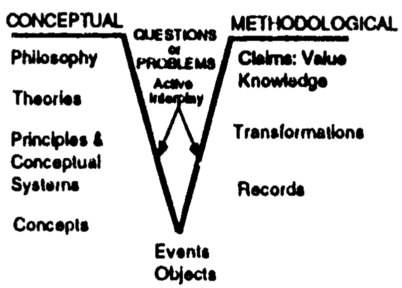


Figure 3: General form of the Vee map (Novak et al., 1983).

Vee Mapping

Vee maps have been proposed for relating conceptual and methodological aspects of science, especially in laboratory settings. Figure 3 shows a general form of the Vee map (Novak et al., 1983).

Roth and Roychoudhury (1993b) reported on the use of Vee maps in a university physics course for elementary education majors. The authors stated that participating students were able "to express their understanding in concept maps" integrated with Vee maps, and "to integrate their knowledge constructed in the laboratory with that constructed during their everyday lives and while reading the textbook". However, students seemed not to benefit much by Vee mapping when studying abstract concepts, representing unobservable entities like electric current. Furthermore, the reported study did not show explicitly the effect of such knowledge organization on students' conceptual understanding, especially on their problem solving skills.

Semantic Networking

Fisher (1990) developed a software (SemNet) intended to help students relate various concepts in semantic networks that would allow: (a) multiple forms of representation, and (b) multiple dimensions of networking. Semantic networking was originally conceived as a "complementary" strategy to concept mapping "for representing and organizing information about a formal domain of knowledge" in structures that are not necessarily hierarchical (Fisher, 1990).

Goldberg et al. (1991) reported on the training of a group of prospective elementary school teachers to use SemNet for learning geometrical optics in interactive tutorial

sessions. Figure 4 shows one typical frame of the SemNet multidimensional network used in the training. It represents the *relations* between one *central concept* (shadow) and *related concepts* (rectangular nodes).

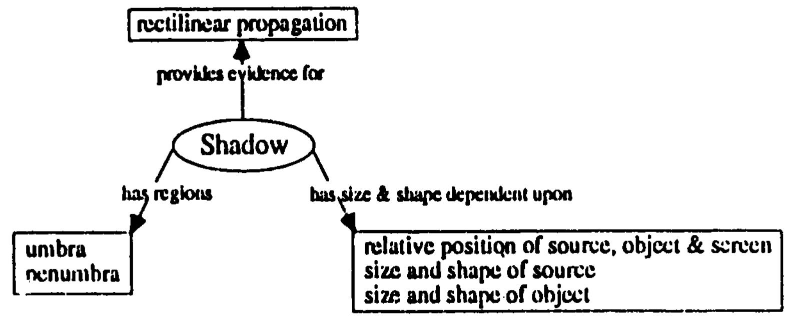


Figure 4: A semantic network relating the central concept of shadow to other concepts (Goldberg et al., 1991).

Another group of prospective elementary teachers from the same class was tutored on the same tasks in a traditional "lecturing" approach that did not make use of SemNet. No difference was detected between the two groups on recall tasks administered after training to the two groups. In problem solving, the group using SemNet performed significantly better only on one task out of three (Goldberg et al., 1991).

All the above modes of presenting scientific concepts concentrate primarily on concept organization, and seldom deal with other dimensions of the structure of individual concepts (discussed below). Furthermore, they all have serious limitations as shown above, especially when applied to physics. No mode was successful enough to warrant an acceptable remedy for students' conceptual deficiency.

Schematism and modeling theory:
An epistemological framework

It has often been argued that holding a university degree in physics (or any other science) is not sufficient for one to become a physics teacher. At issue is not only the need for appropriate training in education, cognition, and the like. More importantly, traditional university physics courses have inherent deficits that are detrimental to physics education. In such courses physics theories are presented as finished products ready to be consumed by students. The conceptual structure of such theories is not made explicit, and neither are their philosophical foundations, especially epistemological ones. Some, like Lakatos (1970), have even argued that "most scientists tend to understand little more about science than fish about hydrodynamics".

This paper is grounded in an epistemological framework that stems from two evolving, complementary works: Schematism and modeling theory. The two could emerge in a single comprehensive theory; this is the objective of a work in progress that is, however, beyond the scope of this paper. *Modeling theory* has been introduced in a separate paper at this NARST meeting (Halloun, 1995b; Hestenes & Halloun, 1995). This theory, as developed so far, concentrates on how models are put together and how they enter into the making of scientific theory. *Schematism*, on the other hand, concentrates on how individual concepts

can be defined and, in a sense, prepared to enter into the making of models. I coined the word schematism from schema and scheme, the development and implementation of which are consistently undertaken by scientists in all their endeavors; a *schema* being a conceptual representation of a pattern inferred by scientists from the structure and/or behavior of specific physical systems, and a *scheme* being a systematic plan devised and implemented by scientists to construct and employ their schemata (which include concepts and conceptual models).

Schematism and modeling theory are underlied by the same philosophical tenets (at least, from my point of view) which we are still in the process of laying out. Below are some ontological and, especially, epistemological tenets that are relevant to this paper. In proposing these tenets, I draw upon major theories in the philosophy of science, without necessarily subscribing to any particular one (Bachelard, in Lecourt, 1974; Bernard, 1865; Bunge, 1973; Carnap, 1966; Eger, 1992, 1993; Franeau, 1973; Giere, 1988; Harré, 1985; Johnson-Laird, 1983; Kuhn, 1970; Lakatos & Musgrave, 1974; Lamy, 1668; Popper, 1979, 1983; Theobald, 1969; Toulmin, 1960; Tuomela, 1973; Ullmo, 1969; Von Glasersfeld, 1989).

Ontology

- There are patterns in the structure and behavior of physical systems that make up the universe.
- Physical systems and phenomena may change in place and time, but the patterns they exhibit are universal and recurrent: they can be detected anywhere and anytime.

Epistemology

- The structure and behavior of physical systems in the universe can be known by humans, at least in some respects and by approximation.
- What we know about the universe depends on the states of: (a) the universe, (b) our mind and senses, and (c) our technological tools, if any.
- Because of patterns' universality, the structure and evolution of the universe can be revealed, in part at least, by studying a few systems exhibiting each pattern.
- Because of the limitations of our human nature and of our technology, all our knowledge about the universe, including scientific knowledge, is tentative and refutable.
- Aspects of the universe that are directly exposed to our senses are often subjective and of secondary nature to science. We often need to imagine how things could be beyond our perceptions in order to build appropriate schemata representing primary patterns in the structure and behavior of physical systems.
- The complexity of our schemata depend on the complexity of what they represent; a schema may be as simple as a single concept, or as complex as a conceptual model.
- The correspondence between a schema and physical systems and phenomena is always partial and approximate. A schema is never isomorphic with what it represents.
- Because no two persons can ever have identical states of mind and senses, schemata are subjective in some respects. However, when conceiving primary aspects of physical systems and phenomena, different persons can reach some consensus and construct objective schemata of similar composition and structure.
- Scientific theories are the result of such a consensus among the members of at least one scientific community. Objectivity of scientific consensus is grounded in empirical

corroboration and the reproducibility of the same experimental results by different groups of scientists.

- A scientific theory is a conceptual system that sets forth: (a) how to ask appropriate questions about the universe, (b) how to answer these questions, and (c) how to evaluate and refine attained answers. Scientific questions can be about describing, explaining, predicting and/or controlling the structure and behavior of existing systems, or about designing and creating new ones.
- Conceptual models are major components of scientific theory; concepts are the fundamental components of such models.
- Concepts of physics are all quantitative. Their quantification is governed by laws and rules that are well-defined in the theory to which they belong. Quantification is a provision for objectivity.
- Scientific language is concise, precise, and objective. Scientific expressions of all kinds are similarly interpreted by concerned scientists.
- Mathematics provide physicists with optimal conceptual tools, including objective communication means.
- Scientific theory sets the rules for employing a concept in various applications.

Schematic structure of scientific concepts

Following the tenets above, every concept of physics (and science) can be explicitly defined within a specific theory by specifying its domain, its organization, and means and methods for its quantification, its expression and its employment.

Domain

The domain of a concept of science consists of ***physical*** objects of the ***real world***. A concept may ***partially*** represent the objects as entities, or it may represent ***one*** property that is common to all these objects. In the first case, it is called an ***object concept***, in the second case, a ***property concept***. Physicists also use logico-mathematical concepts, but these are not concepts of physics; they belong to mathematics.

The concept of particle in physics is an object concept. Its domain consists of all physical objects the dimensions of which: (a) are relatively small by comparison to other objects and to distances separating them (as in the case of atomic particles), or (b) have no significant effect on the behavior of the objects (as in the case of translation in Newtonian mechanics).

The concepts of dimension, mass, and electric charge are property concepts, and so are the concepts of field and force. The former pertain to ***object properties***, the latter to ***interaction properties*** (Halloun, 1995b).

The domain of a given concept may be shared by another concept. However, no two concepts can represent exactly all the same entities in entirely the same respects. For example, students often confuse the property concepts of velocity and speed. In physics, a clear distinction is maintained between the two: velocity is a vectorial concept representing the change of position of a physical object per unit time, speed is a scalar concept representing only the magnitude of this change.

The domain of a concept, especially when a property concept, is reduced as much as possible for precision, objectivity, and simplicity. Centuries ago, Lamy (1668), a French philosopher noted that "une notion est d'autant plus universelle qu'on fait attention à moins de choses" [the less things we concentrate on, the more universal a concept will be].

Teachers need to help students develop ***correspondence rules*** that enable them to delimit the domain of a scientific concept, and determine:

- why and when we need a specific concept;
- what the concept represents in the real world, and under what conditions;
- what it does not represent in the real world.

Organization

An isolated concept is practically meaningless and useless. A concept is always associated with other concepts in scientific theory through appropriate relationships that include axioms, definitions and laws.

Depending on their structural complexity, object concepts of physics can be classified into two classes: simple and composite. Similarly, two types of property concepts can be distinguished: prime and derived.

Simple object concepts are those that represent simple physical entities, like the concepts of particle in physics and point in geometry. *Composite* or *complex* object concepts are those that represent more complex entities like the concepts of solid in physics and polygon in geometry.

Prime property concepts are those that cannot be derived from other concepts, like the concepts of mass, electric charge, force and time. *Axioms* are often used to define prime concepts *implicitly*.

Derived property concepts are those that can be *explicitly* defined in terms of prime concepts and/or other derived concepts. *Definitions* are often used to relate one derived concept to other concepts *of the same nature* (i.e., descriptive or explanatory, object or interaction properties). The concepts of velocity, momentum and kinetic energy are derived, kinematical concepts (descriptive, object properties) that are defined explicitly in terms of other kinematical concepts (position and/or velocity). The concept of work is a derived, dynamical concept (explanatory, interaction property) that is defined explicitly in terms of other dynamical concepts (force or field).

Property concepts of *different nature* are related to each other in *laws*, but never in definitions. For example, Newton's second law relates the dynamical, interaction property of force to the change in the kinematical, object property of momentum (or to acceleration). Laws that relate descriptive concepts to explanatory concepts are often called *causal laws*, in order to distinguish them from other laws that relate concepts of the same nature, like *state laws* and *interaction laws* (Halloun, 1995b).

The organization of any scientific concept is best put in context when used in the *composition* or the *structure* of appropriate models, and in the description and explanation of the *behavior* of these models. Details on such issues are given elsewhere (Halloun, 1995b).

Quantification

A concept cannot belong to physics unless it is quantifiable. Ullmo (1969) even argued that nothing is real until we can measure it. This is not necessarily true for all scientific disciplines, especially biological ones, wherein some concepts remain unquantifiable (at least for now).

Quantification of physics concepts, especially property concepts, is necessary to better understand them and to ensure their objectivity. A century ago, Lord Kelvin (1891) argued:

"when you can measure what you are speaking about, and express it in *numbers*, you know something about it, but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind: it

may be the beginning of knowledge, but you have scarcely, in your thought, advanced to the stage of science".

The ***measurement*** of a property consists of ***comparing*** this property to a particular *standard* with which is associated, by convention and for convenience, the *unit* of measurement. Quantitative measurement of any concept of physics is done according to quantification laws and following quantification rules that are set by the theory to which the concept belongs.

Quantification laws set, among others:

- whether a property concept is scalar or vectorial;
- whether it is extensive or intensive, i.e., whether or not it admits a real zero, and whether or not it is additive;
- whether it can be subject to proportional comparisons;
- the corresponding standard, its unit(s), and the appropriate scale(s) in a conveniently chosen unit system (often the SI);
- the assumptions and constraints underlying a measurement, especially those pertaining to uncertainty, approximation and/or precision.

Quantification rules set, among others:

- how to specify the dimensions of a concept;
- how to convert from one unit into another;
- how to establish the correspondence between a measurement and the real world;
- how to conduct physical measurements in the real world;
- how to estimate errors.

Expression

Objectivity of scientific concepts extends to the way they are communicated among scientists. Physicists express each concept of physics in specific ways that distinguish it from other concepts. Means of expressing a given concept of physics include:

- its *identification*, i.e., its name and the name(s) of its unit(s), all of which are particular to this concept and cannot be shared by other concepts;
- *symbolic labels*, i.e., specific characters that can denote the concept or its units instead of their names, and the appropriate style (e.g., a scalar concept is denoted by a normal letter, whereas a vectorial concept is denoted by a bold letter or a letter with a small arrow on top);
- *pictorial depictions*, i.e., geometric figures that can depict the concept (e.g., the object concept of particle is depicted by a point, and the property concept of velocity is depicted by a vector, a labeled arrow, in an appropriate coordinate system);
- *mathematical representations*, including equations, graphs, and geometric diagrams representing changes in the concept and its relation to other concepts.

Each of the above means of expression is associated with appropriate *semantics* that specify, among others:

- what each expression denotes, especially that each expression form can denote specific features of a concept but never all its features;
- how to interpret each expression and establish appropriate correspondence to the real world;
- how different forms of expression relate to, and complement, each other in specific respects;

Employment

A concept can be used to represent specific physical entities or a common property as specified in its domain, and to construct other schemata. The latter extend from new derived concepts to conceptual models. The employment of any concept is guided by appropriate rules that stem from the above four components of its schematic structure and that are set by the theory to which it belongs.

The most critical part of employing a concept is to decide whether or not it is suitable for an appropriate situation. This choice is guided by the correspondence rules of various concepts. Once a concept is determined suitable, one only needs to *reproduce* part of, or the entire schematic structure of this concept, provided that one has already developed such a structure.

The reproduced schematic structure of a given concept has often to be processed along with other schemata, frequently within the context of a conceptual model. The utility of physics concepts is actually best realized within the context of conceptual models, and in employing them in modeling activities (Halloun, 1995b).

The schematic structure of the concept of force is outlined below for illustration, followed by a summary of major results obtained in training two groups of Lebanese students to use such a structure in solving mechanics problems.

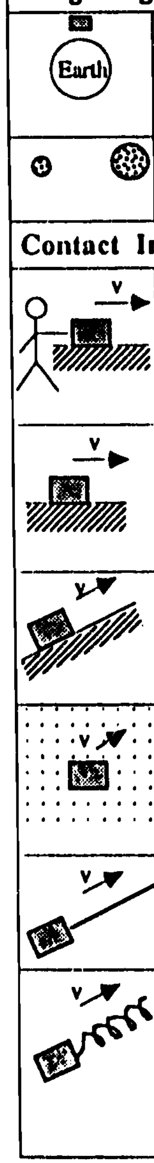
Example: The concept of force in physics

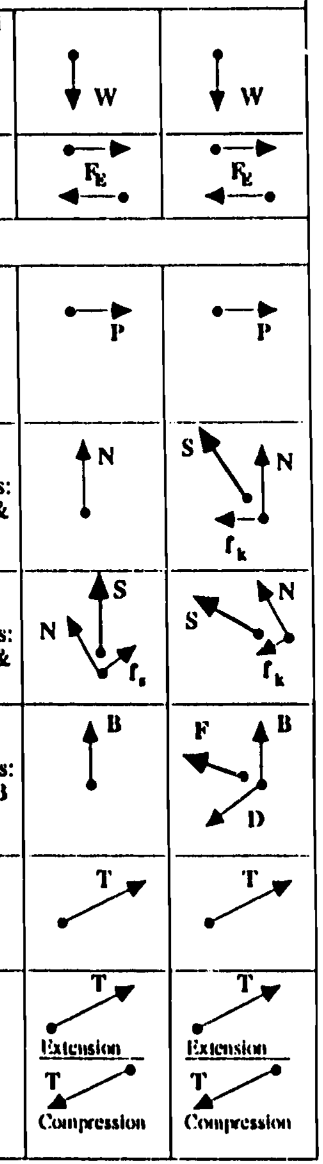
The concept of force is the most fundamental prime property concept used in physics for studying interactions, especially in introductory courses. Prime concepts are harder to conceive than derived concepts. Consequently, they require more attention in instruction than the latter. Research shows that physics students experience unparalleled difficulties in learning the concept of force, especially because they bring along to physics courses their own beliefs about this concept that are incompatible with scientific theory (Halloun & Hestenes, 1985b; Hestenes et al., 1992). For all these reasons, I have chosen to illustrate the proposed schematic structure of scientific concepts with the force concept.

Domain

The concept of force is a *property concept* that represents an *interaction* between two physical objects. Hence, all interacting physical objects belong to the domain of this concept. Four fundamental types of interaction are distinguished in physics: gravitational, electromagnetic, strong and weak. Each type is associated with a specific object property, e.g., mass and electric charge for gravitational and electromagnetic interactions respectively. Not all physical objects undergo all four types of interaction. Hence, the domain of the concept of force can be divided into four subdomains. Each subdomain contains physical objects that experience a specific type of interaction. Some objects may belong to more than one subdomain.

In introductory classical mechanics courses, another kind of interaction classification is commonly used for convenience, and a specific type of force is associated with a specific set of agents. An *agent* is a physical entity that interacts with another physical entity, an *object*, the state of which is being studied. Two types of interaction in such courses are commonly distinguished: (a) long-range interaction or interaction at a distance, and (b) contact interaction. Figure 5 shows some of the most common agents and respective forces, along with vectorial depictions (discussed below) of such forces when exerted on particle-like objects.





Agent Name	Agent Examples	Force Name
Long-range Interactions		
Any physical object	Earth, Moon, Sun, other planets	Gravitational force or Weight W
Electric charge carriers	Electrons, protons, ions, macro-objects	Electrostatic force F_E
Contact Interactions		
Direct mover	Human hand, one car directly pushing another car	Traction: Push, pull P
Horizontal Solid Support	Table, ground, road, shelf, board, human hand	Support force S. Components: Normal N & friction f
Inclined Solid Support	Table, ground, road, shelf, board, human hand	Support force S. Components: Normal N & friction f
Fluid	Air, water, other gas / liquids	Fluid force F. Components: Buoyancy B & drag D
Rigid Suspender	Rigid rope, string, rod, bar, or chain, human arm	Tension T
Elastic Suspender	Spring, Elastic rope, string, rod, bar, or chain	Restoring force T

Figure 5: Common agents in particle mechanics and respective forces

Correspondence rules associated with the force concept specify that:

- the concept of force is needed to represent an interaction between two physical entities: an *object* and an *agent*;
- a force represents one side of the interaction, the action of an agent on an object, or that of the latter on the former; both (opposite) forces are always involved in any interaction;
- an object cannot interact with itself, and every force must have an agent; hence, unless an agent exists that interacts in a specific way with a given object, the concept of force cannot be used;
- the existence of an interaction, and hence the need for the concept of force, can be recognized from the state of an object: a particle of constant momentum (or velocity) is a free particle that may not be interacting with any agent; however any change in its momentum requires an interaction with one or many agents;
- no intermediary between an object and an agent is needed for them to interact (this is true at the macroscopic level but not necessarily at the microscopic level);
- the concept of force is an explanatory or dynamic concept; it explains the change in the momentum (or velocity) of an object;

Organization

The concept of force is a prime property concept. It cannot be presented explicitly in a definition. Newton's 2nd law is sometimes believed to provide a *definition* of the concept of force. It does not. This law is just that: a law, not a definition. All Newton's laws combined can provide an axiomatic definition of the concept of force. For this reason, they are sometimes referred to as axioms of force.

Interaction laws, such as Newton's law of universal gravitation, Coulomb's law of electrostatic interaction or Hooke's law, relate the concept of force to specific object property concepts. Causal laws, such as Newton's second law, and conservation laws relate the concept of force to *changes* in some of these property concepts. Other dynamical concepts, like the work concept, derive from the force concept and can be explicitly defined in terms of it. Appropriate models that use such definitions and laws put the concept of force in full perspective (Halloun, 1995b).

Some researchers have shown that hierarchical organizations involving the concept of force can improve student understanding of mechanics (Reif & Larkin, 1991). No evidence has been provided to show the impact of such organizations on understanding the concept of force specifically. However, one can infer that, if carefully designed, a hierarchical organization can be one effective way for partially showing how some physics concepts are related to the concept of force. Such an organization, though, can only be one tool among many other needed tools; it is by no means sufficient for learning any concept.

Quantification

Quantification laws associated with the concept of force state that:

- it is a vectorial concept, and hence its measurement requires the specification of a direction (Figure 5), a magnitude and a unit which is the Newton (N) in SI;
- it is an extensive concept, i.e., a single force of magnitude zero indicates no interaction;
- it is additive vectorially following the superposition principle;
- two forces can be compared by a ratio;
- the concept of force is indirectly measured physically; there are no direct means (or physical probes) for comparing a given force to a standard force in the same way, say, the length of an object is physically measured by comparing it to the gradation of a

ruler; a force is always measured through its effect on a given object, like stretchi compressing a spring;

- changing the strength of an interaction between an object and an agent induces a proportional change in a given state property of the object; two forces are then axiomatically said to have equal magnitudes if they produce the same effect on th object; this is underlined by the assumption that after each measurement, the sam object can be brought exactly to the same initial conditions;
- the magnitude of a force can be related to the value of some object property of th interacting objects as given by interaction laws, such as Newton's law of univers gravitation or Coulomb's law of electrostatic interaction.

Quantification rules set, among others:

- the dimension of a force which can be given symbolically by:

$$[\text{Force}] = \frac{[\text{Mass}] \times [\text{Length}]}{[\text{Time}]^2}$$

- how to convert from SI to the cgs or the old British unit systems, knowing that: 1 dyne = 10^{-5} N (cgs) and 1 lb = 4.448 N (Brit.);
- how to determine the characteristics of a force exerted by a given agent;
- how to measure a force physically using appropriate force probes (e.g., spring s
- how to establish the correspondence between "reading" an effect and the magnit the force that causes it;
- how to estimate errors in an experimental setting.

Expression

The concept of force is expressed according to the following:

- "Force" denotes only the concept representing an interaction between two physic objects as outlined in the domain section above, and "Newton" denotes the corresponding unit in SI;
- Symbolic labels include bold letters or letters with small arrows on top for a for "N" for the Newton unit;
- A force is pictorially depicted by a vector, a labeled arrow, in an appropriate coo system (Figure 5); specific assumptions underline the point of application of thi vector, depending on whether or not the object is particle like;
- A force can also be represented mathematically with equations or graphs relatin other concepts as discussed in the *organization* subsection.

Among the semantics associated with the concept of force are the ones that spec

- that a normal letter labels the magnitude of a force, whereas a bold letter labels i direction as well;
- how to interpret a given depiction or representation of a force, e.g., how to tell magnitude and direction of interaction between an object and an agent from the corresponding force vector;
- how a force vector can only depict a force at a given instant, and how changes i direction and magnitude may be better represented by appropriate diagrams suc field lines, graphs and/or equations.
- how to interpret a given mathematical representation, e.g., how to interpret the in "**F** = m**a**" as relating a force **F** exerted by an *agent* to its effect **a** on an *object*

m, and how this relation of equality differs from one expressed say in "a = dv / dt" for defining the acceleration of an object in terms of its own velocity;

Employment

The employment of the concept of force is governed by the above four components of its schematic structure and the models in which it is being used. In the case of classical mechanics, Figure 5 provides some guidelines for identifying agents interacting with a specific object and depicting the corresponding forces. Students need also to develop and follow other guidelines for using the force concept in solving mechanics problems. In the case of particle models, for example, students need to learn:

- how to identify each object and represent it by an appropriate particle in a conveniently chosen inertial reference system;
- how to depict the reference system by a convenient coordinate system, and the particle by a point in this system;
- how to identify agents, remembering that, except for the Earth and charged particles, no physical entity can be an agent unless it is in contact with a given object;
- how to identify the force exerted by each agent on a given object;
- how to depict this force by an appropriate vector in a force diagram, and how in such a diagram it is convenient to ignore the forces exerted by the object on its agents;
- how to depict all forces exerted on a particle like object by vectors whose common tails coincide at the point depicting the particle;
- how to resolve a force vector in appropriate components, and how to compose many force vectors following the superposition principle;
- how to match various mathematical representations of this concept and how to conduct appropriate operations with those representations;
- how to match the resultant force on an object with the acceleration of the object;
- how to choose between Newton's laws and the work-energy principle to relate the resultant force to its effect on each object.

Similar guidelines need to be developed for using the concept of force in studying other types of models. Details stemming from the generic modeling process can be found elsewhere (Halloun, 1995b).

Preliminary evaluation of the schematic force concept in training Lebanese students

The schematic structure of the concept of force was partially assessed in training two groups of Lebanese students. One group consisted of 59 high school students who failed an introductory physics course, the other of 25 college students. Each group was trained during five two-hour sessions to solve particle mechanics problems following a modeling approach. Details of this approach and of the training method and results are given elsewhere (Hestenes & Halloun, 1995).

Figures 6 and 7 compare trained students' performance on parallel pretest and posttest problems. Figure 8 compares the performance of Lebanese college trainees to that of a group of 139 U.S. college students on the linear motion problem (Figure 7). The last group received traditional physics instruction that did not follow a modeling approach. In an independent study involving students enrolled in the same courses at the same Lebanese and U.S. institutions, it has been shown that U.S. students were at a higher competence level than Lebanese students (Halloun, 1986). As can be seen in figures 6, 7, and 8, training students to develop the schematic structure of the concept of force and employ it in solving statics problems (high school group) and particle translation problems (college group) helped improve significantly their problem solving abilities.

Major outcomes of this limited research that are worth outlining here are:

- Identification of correct agents was necessary for all trainees to identify and depict the correct forces acting on a given object. All students who failed to identify agents first, and those who committed mistakes while doing so drew wrong force diagrams.
- On the pretests, trainees often showed superfluous forces that actually did not exist; such was virtually not the case on the posttests. Most college students in the traditional group (Figure 8) committed such mistakes.

  Understanding the domain of the force concept and the information in Figure 5 were critical in both respects above.
- All college trainees who drew correct acceleration vectors (72%) for the linear motion problem were able to depict forces in correct force diagrams, especially the force of friction exerted by cart C on load A. Only 4% of college students in the traditional group were able to draw correct force diagrams (Figure 8). Virtually all other students in this group who depicted the friction force in question drew an arrow in the opposite direction.

  Matching various depictions for the same situation was thus critical for identifying the correct dimensions of a force.
- All college trainees and 88% of high school trainees who showed a correct force diagram were able to write the correct equation representing Newton's second law for the corresponding situation ("translational equilibrium" in Figure 6, and "causal laws" for the linear and circular motions in Figure 7).

  Correct depictions were thus critical for relating concepts in appropriate laws (organization means).
- Trainees who were able to choose the correct laws and write correctly the corresponding equations, but failed to complete the solution to a problem, did so because of mathematical deficiencies. Mainly, they failed to resolve a force vector into components or evaluate these components, and/or to compose many force vectors or evaluate their resultant.

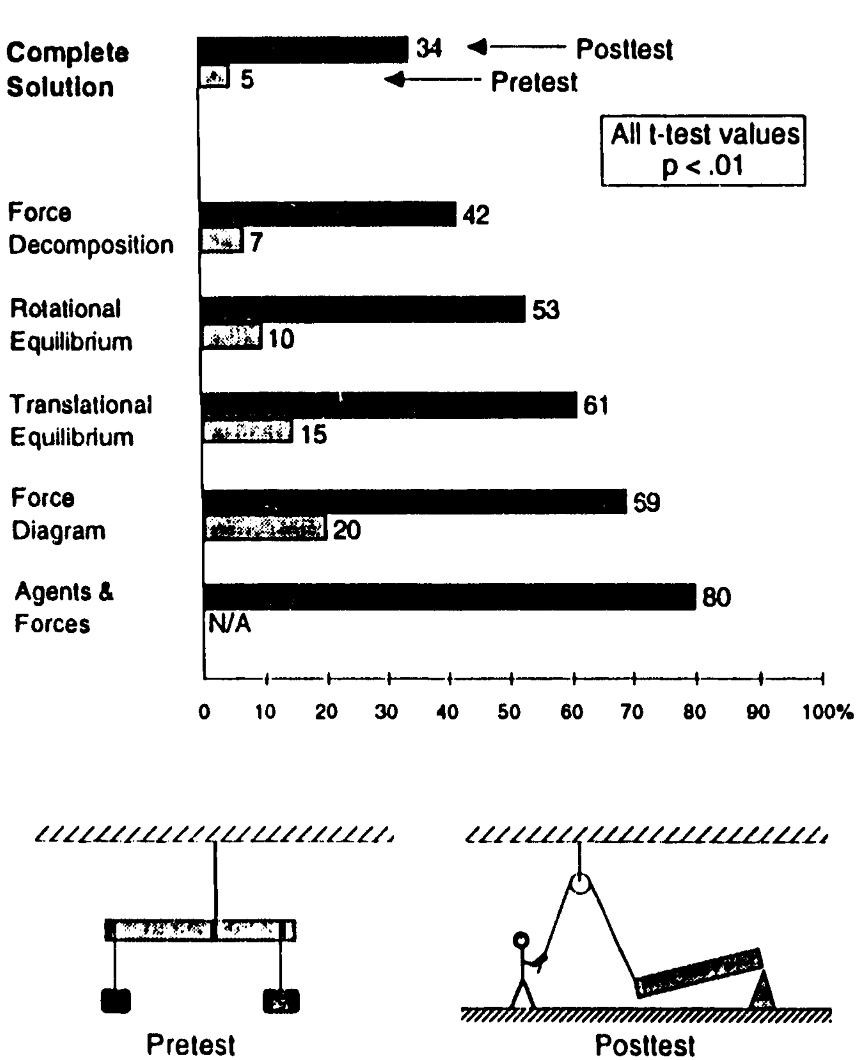
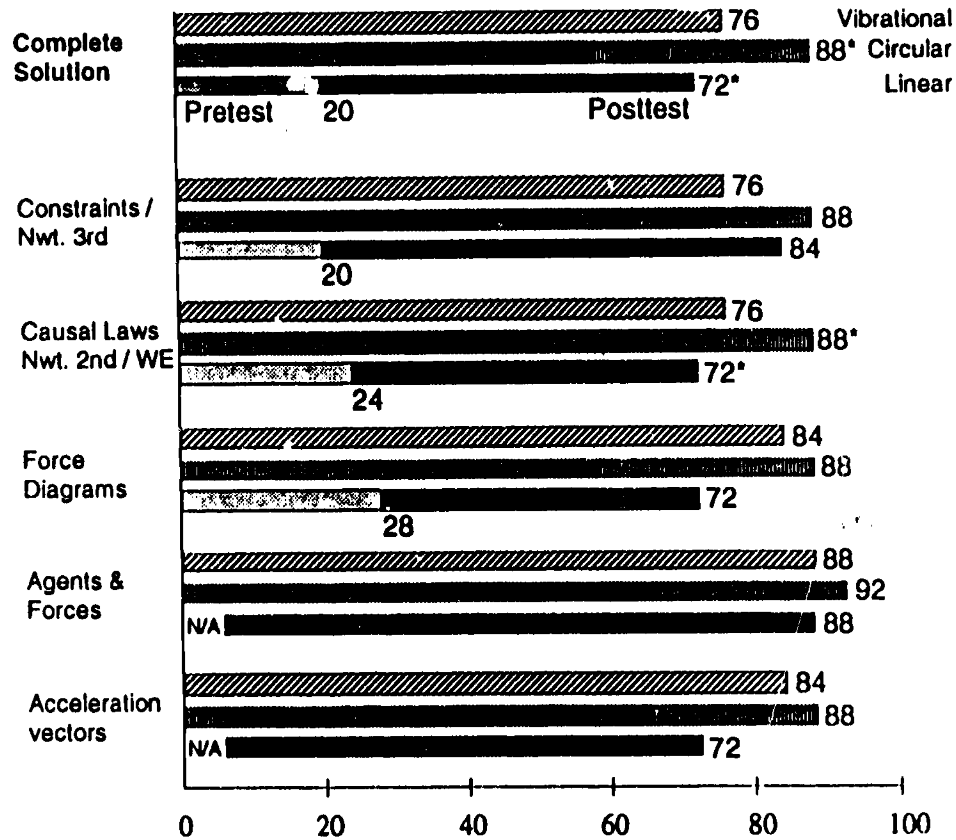


Figure 6: Percentages of high school trainees who presented correctly specific components of the solutions of a pretest problem (bottom bars) and a posttest problem (top bars); the situations of the two statics problems are depicted above.



* All students who did correctly the a & F vector diagrams completed tasks indicated with a star

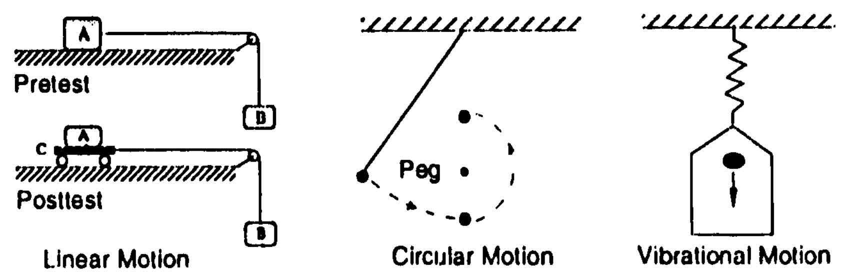


Figure 7: Percentages of college trainees who presented correctly specific components of the solutions of three posttest problems the situations of which are depicted above. Trainees' performance on a pretest problem of linear motion is also shown in the left portions of bottom bars.

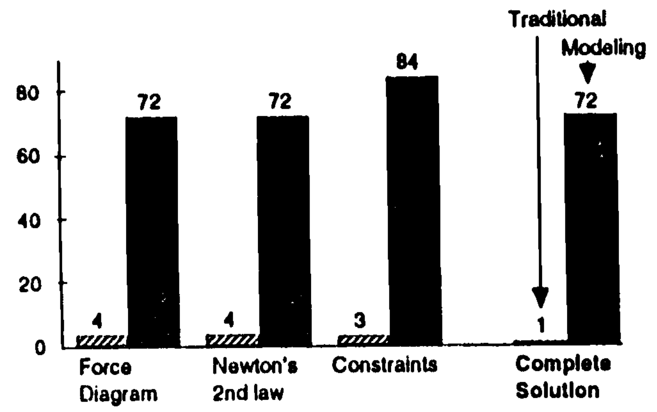


Figure 8: Percentages of Lebanese college trainees (right bars) and U.S. students (left bars) enrolled in a similar traditional college physics course who presented correct components of the solution of the posttest linear motion problem of Figure 7.

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